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Hybrid joints of polymer and thin metal parts fabricated by laser technology: performance under realistic conditions

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Abstract

Direct thermal joining of polymeric and metallic materials is currently arising as an alternative technology for the generation of hybrid joints. The focus of this study is on developing hybrid joints of polymethyl methacrylate PMMA and thin AISI430 parts by laser technology and the analysis of their performance under operating conditions required by home appliance applications. Mechanical resistance, mechanical stability at thermal shocks, salt spray tests and aesthetic requirements have been addressed. Firstly, the thin metal part was locally structured by pulsed laser radiation producing micro-patterns to improve the adhesion of the PMMA part. Secondly, the polymer-metal interface was irradiated by a Continuous Wave fiber laser by transmission method to achieve the joint between both materials. The assessment of mechanical stability at 400 thermal cycles up to a peak temperature of 85ºC is a real challenge considering the remarkable differences in terms of thermal properties of both materials.

Keywords: polymer-metal hybrid joints; laser joining; laser surface modification

1. Introduction

In the last decade, laser technology is starting to be considered for the joint of polymeric and metallic materials in different contexts with scope mainly in the automotive and medical device applications.

The laser joining approach was first tried at the Joining and Welding Research Institute of Osaka University by Kawahito, Y. et al, 2006 and Katayama et al., 2007 . In these pioneering studies, joints between stainless steel and PolyEthylene Terephthalate (PET), PolyAmide (PA), PolyCarbonate (PC) and PolyPropylene (PP) were generated. High tensile shear strength was achieved, suggesting the presence of both chemical

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and physical bonding. Since then, the technique has been extended to various material combinations, such as DC01 (SAE 1008) steel to PA6.6 by Bergmann J.P. et al., 2012, aluminium to PC, PA and glass fibre reinforced PA by Amend P. et al., 2013, AISI 304 stainless steel to PolyMethilMethacrilate (PMMA) by Hussein F. et al. 2013, zinc – coated steel to carbon fibre reinforced PA by Jung K.W. et al., 2013 and stainless steel to Cyclic Olefin Polymer (COP) by Grujicic M. et al., 2008.

However, other approaches for polymer–metal hybrid joining were revised by Gruijic M. et al. 2008, concluding that the one based on micro-scale mechanical interlocking is the most promising method. The origin of this interlocking with the melted polymer was the previous generation of micro-patterns on the metal surface, producing surface irregularities. Therefore, the control of these surface irregularities becomes significant for hybrid polymer-metal joints, being laser ablation with pulsed sources one of the most advanced techniques used for this purpose. For the last eight years, several studies have been reported based on the effect of laser structure parameters on the mechanical properties of hybrid polymer-metal joints. Roesner A. et al. 2013 and Van der Straeten K. et al., 2016 reported the effect of structure density or geometry generated during the laser metal micro-structuring on the mechanical behaviour of hybrid joining (steel-reinforced PA) conducted by induction technique and laser technique respectively.
Amend P. et al. 2014 explored the direct joining between aluminium and PA6, performed by means of mono- and polychromatic radiation with the micro-structuring process produced by ns-pulses. Heckert A. and Zaeh F. 2014 reported the potential of laser processed surface structures in the macroscopic, microscopic and nanoscopic scale as metal pre-treatment for the subsequent thermal joining process of three fibre reinforced thermoplastics with aluminium.

Many efforts have also been done to understand the laser hybrid joining mechanisms by different characterization techniques like SEM, EDX, XRD and XPS by Chi-Wai Chan et al. 2016 and thermal defect zones of the joint were analysed by laser confocal microscope. The result showed that a thermal defect zone was generated in the stainless-steel surface, which would affect the metal mechanical property and reduce the component service life. The study of Jiao J. et al., 2018 reports thatthe influence of the laser joining parameters on the thermal defect zone size and the joint strength was relevant.

Furthermore, this metal modification by laser ablation process has also provided significant surface enlargement for high strength and durable mechanical bonding in adhesive joint in several ways in the aeronautical sector. Bond strength improves due to (i) increase in surface area, (ii) mechanical locking, and (iii) improvement in wettability of adherend interface enhancement of adhesive joint strength by laser surface modification, Baburaj E.G. et al. 2007. Other more recent researches, Rotella G. et al., 2015, have delved into the laser modification with different patterns of ablation and the comparison of their ratios of productivity for the aforementioned sector.

In two previous publication from the authors, Rodríguez-Vidal E. et al. 2016 and 2018, the effect of geometric structures conducted by pulsed and CW laser radiation on metal parts on the mechanical behavior of steel-reinforced PA T-joints and lap-joints was analyzed along with the examination of the failure modes. The joining operations were conducted by CW laser radiation. Although previous studies demonstrated the beneficial effects of modifying the metal surfaces on the hybrid joint´s mechanical performance, there have been no investigations focused on further characterization of the durability of the joints treated by laser.

In the present work, not only the mechanical performance of the lap-joint is analyzed through 3-point bending tests but also the corrosion and thermal resistance of the assembly after laser treatments. These last tests were carried out according to home appliance sector standards. The metal is pre-treated by a nanosecond pulsed laser radiation (λ = 1064 nm) to avoid damage on the thin metal strip whereby a controllable micro-structured surface is generated, while the joining step was carried out by Continuous Wave (CW) laser radiation (λ = 1064 nm).

2. Experimental

2.1. Polymer-metal assembly by laser technology

Materials used in this work were polymethyl methacrylate (PMMA) and stainless steel (AISI430). Samples dimensions were 80x25x0.5mm and 80x25x3.3mm for metal and polymer respectively.

Metal specimens were laser structured with selected texture patterns by a nanosecond fiber laser source (Figure 1a). Laser beam movement was produced by a 2D galvo scanning system, capable of scanning structured pattern at high speed. A total surface of 15x20mm^2 was structured on the metal samples by means of single parallel groove oriented perpendicular to the long edge of the plates. Non-contact topographic measurements of micro-structures were conducted using confocal microscopy (Sensofar S-Neox).

Subsequently the polymer-metal interface was irradiated by a laser transmission joining using a CW fiber laser source. In this operation, the laser beam is also guided and focused on the workpiece by a 2D galvo scanning unit. The laser energy is first absorbed on the metal surface and then transferred to the polymer interface with which is direct contact, generating the melting of the polymer and producing the joint after solidification (Figure 1b). Both materials were clamping by applying a uniform pressure (P=2bar) with a pneumatic clamping device, in order to enhance the flow of the molten plastic material into the microstructures of the steel. A borosilicate window was placed on the upper part of the assembly to ensure homogeneity along the joining area. Three different joint configurations were developed (Figure 1c): three point bending and corrosion tests and the assessment of mechanical stability after thermal shock cycles considering joining areas of 400mm^2, 200mm^2 and 570m^2 respectively.

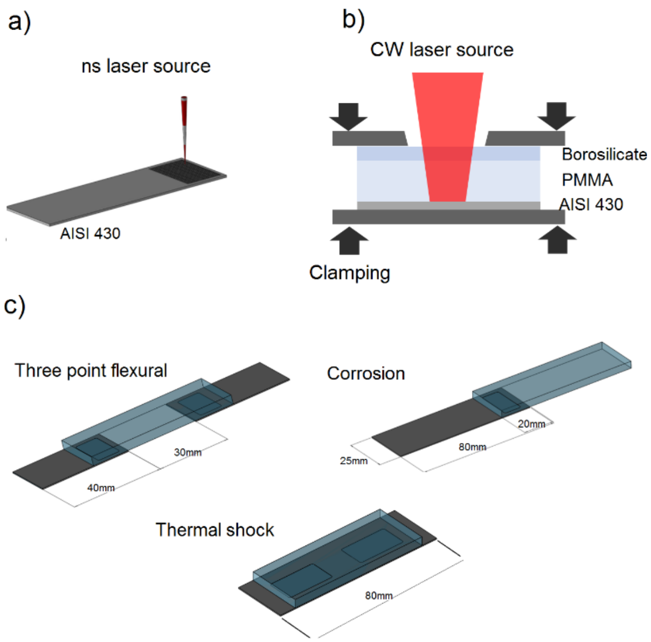

Fig. 1. Scheme of a) texturing process; b) joining process; c) joint configurations.

2.2. Joining characterization

Mechanical testing was conducted using an INSTRON tensile machine (3369 Static Universal) equipped with a 3-point bending system and a 50kN load sensor (Figure 2). The distance between supporting pins is 84mm and a cross-head compression speed rate of 5mm/min. Four specimens were tested per each experimental condition to ensure the reproducibility of the results.

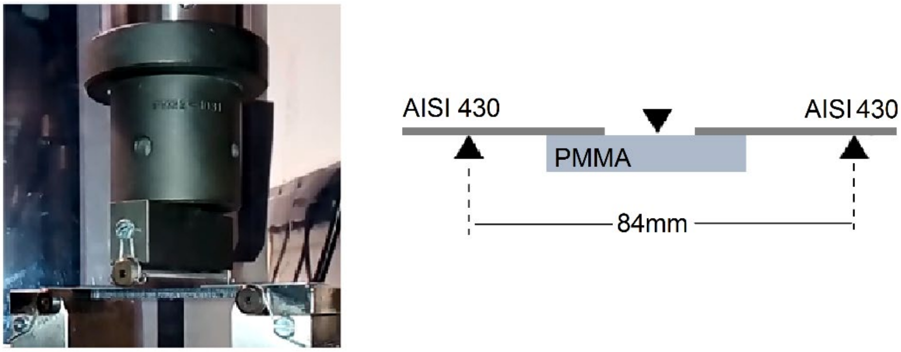

Fig. 2. Experimental device with a tested sample and scheme

Corrosion tests were performed in a three-electrode electrochemical cell using a Ag/AgCl (KCl 3M) reference electrode (SSC) and platinum wire counter electrode both connected to a potentiostat Metrohm Autolab PGSTAT 30. As corrosive media, a standard solution of NaCl 0.06M was used as electrolyte. After immersion of joined area into the corrosive solution, the Open Circuit Potential (OCP) started to be registered for an hour to allow its stabilization. After the first hour of immersion, a linear polarization was carried out from -0.4 V (vs OCP) to +0.6V (vs OCP) at a scan rate of 0.5mV/s. The exposed area of the samples was 300mm^2. Tests were performed in triplicate.

Joined samples in full-overlap configuration (Figure 1c) were considered for thermal shock tests. The joined samples were undergone to 400 thermal cycles tests in a warming oven with air circulation and temperature control (±5ºC). The temperature cycle was: 2h ON and 2h OFF. After every 100 cycles of heating and cooling the joining areas were examined in order to identify possible visible changes and mechanical impairments.

3. Results

3.1. Polymer-metal assembly by laser technology

The microstructure patterns, consisting of parallel grooves, were defined in terms of groove depth (*d* in Figure 2a), groove width (*w* in Figure 3a) and the distance between adjacent grooves (d_{c-c} in Figure 3a). Different micro-pattern geometries of grooves were considered changing the marking parameters and keeping constant the laser parameters: 40W average power level, 170ns pulse duration and 41kHz repetition rate. Table 1 gathers the marking (N_{tracks}, d_{c-c}) and topographic (d, w) parameters for the nine different micro-textures analyzed in the study. The different sets of laser parameters guarantee the steel thin sample does not bend as consequence of the thermal effect of the laser radiation. The groove topographies are characterized by a well-defined depth and width values along the pattern (Figure 3b). Additionally, a significant present of recast material (recast material height around 30µm) is observed at the structure border as consequence of the thermal effect of short pulses on the steel plate. Topographic parameters of the considered micro-patterns (Table 1) disclose that groove depth (d) increases with increasing number of tracks while groove width (w) remains constant for N_{tracks}=2 and 6 and decreases for N_{tracks}>6. This fact is related to the increase of ejected material from the cavity, which is redeposited on the edges of the grooves.

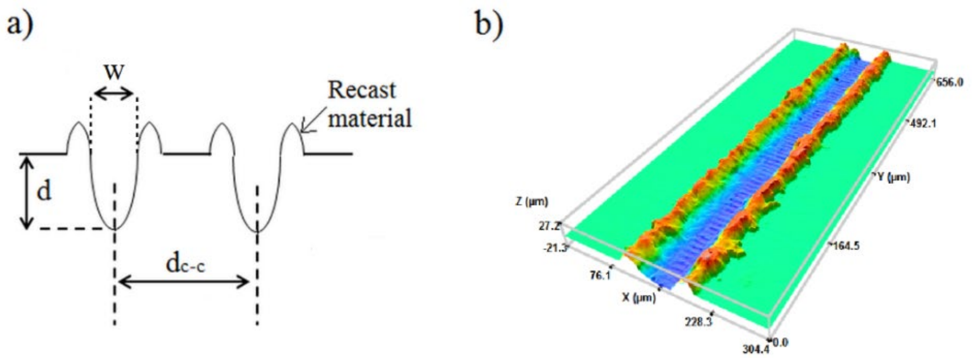

Fig. 3. (a) Schematic laser structure surface; (b) confocal topography for N_{tracks}=2 (R3).

Table 1. Micro-pattern geometries

Micro-pattern Reference	N_{tracks}	dc-c [µm]	d [µm]	w [µm]
R1	2	300		
R2	2	600	13	50
R3	2	900		
R4	6	300		
R5	6	600	40	50
R6	6	900		
R7	10	300		
R8	10	600	80	30
R9	10	900		

3.2. Joint performance characterization

After metal micro-structuring, the specimens were joined also by laser technology and mechanically tested by three point bending tests (Figure 4a) to measure flexural properties, joint failure force and failure initiation mechanism. The flexural stress-strain responses of the hybrid polymer-metal joints were obtained for the nine micro-patterns.

All hybrid joints presented interfacial mode reaching maximum loads of around 100N with maximum standard deviations of around 18%. Figure 4a discloses similar trend of maximum load before metal bending of the three considered groove geometries as function of the distance between patters. Maximum load increases with decreasing the distance between grooves which could be explained based on the higher amount anchoring micro-structures.

For a certain micro-structure geometry (Figure 4b, N_{tracks}=6) decrease of distance between grooves involves a meaningful increase of the flexural properties of the joint before failure. The latter could be related to the fact that a high amount of melted polymer was hooked into the grooves which comprises a better anchorage between parts delaying the detachment between parts.

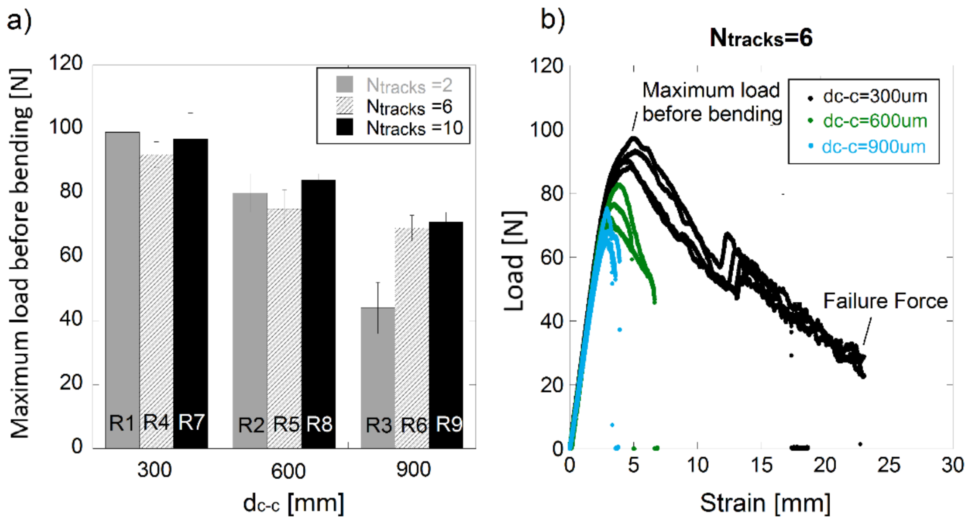

Fig. 4. (a) Failure force for three point bending tests; (b) Stress strain curve for AISI430 samples with micro-patterns R2, R5 and R8.

For d_{c-c}=300 and 600µm the results not evidence a direct impact of groove geometry on the flexural properties of the hybrid joint. The role of the groove geometry (N_{tracks}) seems to be significant for high distance between patterns (dc-c=900µm) which could be a consequence of a dominate effect of groove geometry for low groove density values.

Based on the hybrid joint's mechanical performance, the set of micro-structure parameters selected for developing the next stage of hybrid joints was R1: maximum load and before bending maximum along with maximum deformation of joint before joint failure.

In order to evaluate if the two laser treatments (texturing and joining) have a detrimental effect on the corrosion resistance of metal part, electrochemical corrosion tests were carried out in the laser treated area and in a remote area of the metal part (untreated). After polarization tests, different kinetical parameters (corrosion current, pitting potential and corrosion resistance) were calculated and compared.

Figure 5 shows the potentiodynamic polarization measurements of untreated and laser treated metal surface after texturing and joining processes. Both curves are quite similar and smooth, indicating that corrosion resistance is not affect by laser treatment. The results evidences that corrosion current $((i_{corr})_{untreated}$= 35µA/cm2 and $((i_{corr})_{treated}$= 63µA/cm2) and corrosion resistance $((R_p)_{untreated}$=322kOhm and $(R_p)_{treated}$=194kOhm) are similar for both surfaces. Corrosion parameters (R_p, I_{corr}) obtained on laser treated area the usual values for this type of stainless steel in contact with NaCl, reason why the process of union metal-polymer did not affect the corrosion resistance of the steel.

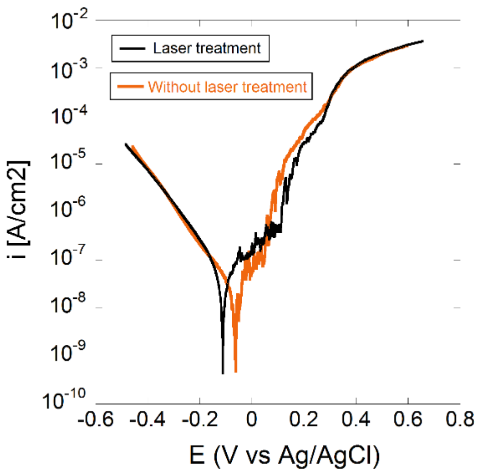

Fig. 5. Polarization curves of AISI430 in NaCl 0.06M solution

Hybrid polymer metal samples under configuration described in Figure 1c were prepared for thermal shock tests. As in the case of corrosion tests, pattern corresponding to microstructure parameters R1 was considered as metal pre-treatment and also joining parameters were kept constant for this new joint configuration. As dissimilar materials, PMMA and AISI430 have significant different coefficient of thermal expansion:$\alpha_{PMMA} \approx 10^{-6}K^{-1}$ [-30ºC, 23ºC] and $\alpha_{AISI430} \approx 10x10^{-6}K^{-1}$[20ºC, 100ºC]. It involves different behavior of parts during cooling which lead different tensions contributions that tend to reduce the interlock of the polymer-metal joint. In this research, joining area of hybrid assemblies was optimized to minimize the described detrimental effect under thermal shock cycles. Figure 6 shows that hybrid assembly does not exhibit bending effects neither detached zones after 400 thermal cycles. Mechanical tests after thermal cycle tests are in process to assess the mechanical interlock 's performance between both materials.

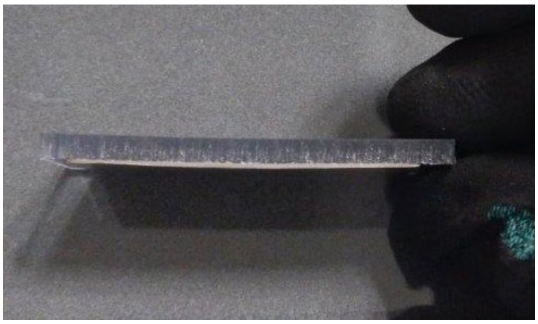

Fig. 6. Hybrid polymer-metal joint after 400 thermal shock cycles

4. Conclusion

Thin steel surfaces were micro-structured by pulse laser radiation prior to the joining process with thick PMMA samples. The joining process was carried out by CW laser radiation. The effect of different micro-patterns on the joint's flexural performance was assessed. The most promising micro-structure was consider for testing the hybrid assemblies under corrosion and thermal cycles tests according to home appliance sector standards. Results evidenced unchanging performance of corrosion resistance of the metal part after laser treatments. Not bending effects neither detached joining zones of the hybrid assembly after 400 thermal cycles were observed.

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